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Orbiter Fuel Cell Performance Constraints

STS/OPS Pratt/Whitney Fuel Cells

Operating Limits for Mission Planning

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SHUTTLE PROGRAM

ORBITER FUEL CELL PERFORMANCE CONSTRAINTS

STS/OPS PRATT/WHITNEY FUEL CELLS

OPERATING LIMITS FOR MISSION PLANNING

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1.0 INTRODUCTION

The Shuttle Operational Data Book (SODB) constraints will be exceeded by several Space Transportation System/Operation Project Shuttle (STS/OPS) activities requiring large power demands; i.e., prelaunch, ascent, and deorbit. This document presents the results of an evaluation of the Orbiter Fuel Cell Powerplant (FCP) performance constraints listed in the SODB (ref. 1). The analysis was performed using the Shuttle Environmental Control Requirements Evaluation Tool "SECRET" developed by the McDonnell Douglas Technical Service Company of Houston. The analysis incorporates the effects of FCP lifetime, thermal (coolant loops) and FCP voltage output on FCP performance.

2.0 SUMMARY

Current electrical power systems mission analysis by the Consumable Analysis Section for the STS/OPS missions indicate FCP usage will exceed existing Orbiter FCP performance constraints defined in reference 1. This document outlines analyses performed to evaluate these constraints. The results indicate FCP limits, as defined in the SODB, are no longer valid, and changes should be made to reflect current design limits. These changes, if incorporated, will relax the FCP constraints such that current mission design and resultant power levels will not violate the real FCP limits. This evaluation incorporates limits for FCP lifetime, thermal (coolant loops), and FCP voltage output. A matrix is provided to illustrate this analysis result for FCP output limits.

3.0 DISCUSSION

The evaluation of the FCP performance limits has been performed to determine if the SODB constraints could be modified because each of the STS/OPS missions will require power in excess of the current power limits during prelaunch, ascent, and deorbit.

The predicted power range taken from reference 2 of the STS/OPS missions will range between 14 and 36 kilowatts. A typical mission power profile is presented in figure 1.

The SODB performance constraints identified for the FCP taken from reference 1 are as follows:

a. The active thermal control system (ATCS) FCP heat exchanger has a design requirement to furnish between a minimum of 40°F and a maximum of 140°F in the FC-40 coolant loop inlet into the FCP.

b. The FCP power output constraints per fuel cell are 7 kilowatts continuous, 10 kilowatts for 1-hour maximum, 12 kilowatts for 15 minutes every 3 hours and 15 kilowatts for 12 minutes maximum.

   The SODB defines a three-FCP continuous output of 21 kilowatts as being acceptable. Any increase in operating output above 21 kilowatts will cause FCP damage or deterioration to the system. This FCP power output constraint is assumed to be determined by the thermal limits within the fuel cell and/or the ATCS coolant loops ability to remove heat.

c. Maximum system power output must not exceed 24 kilowatts for more than 2 minutes (two FCP's).

The following assumptions were used in the evaluation of the FCP constraints:

a. The maximum temperature limit into the FCP via the FC-40 loop is 140°F.

b. Only the maximum FCP power output constraints will be evaluated.

c. All three fuel cell power outputs are equally shared.

d. Spacelab 8-panel radiator configuration is assumed.

e. The Freon 21 will have a flow rate through the FCP heat exchanger of from 5300 to 5854 lb/hr with 2 loops operating and from 2650 to 2927 lb/hr with one loop operating, depending on flow configuration.

f. The radiator and flash evaporator combined deliver an outlet coolant temperature of 39°F.

The initial phase of this analysis was performed with the above assumptions to determine the FCP performance limits that are determined by the coolant fluid systems in transporting and rejecting the heat created in the FCP itself and by the activated equipment utilizing the power. There are three fluid systems tied together by interchangers and heat exchangers that collect this heat and reject it via radiation and evaporation in the ATCS loop (see thermal flow as presented in figure 2). By assuming the maximum inlet temperature of 140°F into the FCP and determining the flow rate of the coolant loops, one can determine the maximum permissible power level that the system can accommodate. Figure 3 presents the maximum permissible fuel cell total power output in kilowatts versus ATCS flow rate. Heater operation is another variable that must be considered. Heat generated by heaters is not rejected via the coolant loops; therefore, if heaters represent 15 to 25 percent of the total EPS load, the FCP can be operated at higher power levels, approximately 48 kilowatts as indicated by figure 3. Several contingency conditions were evaluated; these cases were set up with coolant loop/fuel cell failure conditions. Figures 4 through 6 present the following FCP performance limits with one ATCS loop and three fuel cell loops, one ATCS loop and two fuel cell loops, and one ATCS and one fuel cell loop. Figures 3 through 6 should be considered the ATCS-imposed thermal constraint on FCP operation during STS planning and incorporated into the SODB. Additional limits may be imposed by the FCP stack temperature; these limits are not addressed in this document. Current STS/OPS power requirements are not exceeding the limits defined in figure 3.

There are several other operating constraints, however, that will impact FCP operating levels prior to reaching the constraints discussed above. They are FCP voltage output, ATCS heat rejection and other equipment thermal limits, and fuel cell lifetime.

3.1 FCP VOLTAGE OUTPUT

The FCP voltage output must be maintained between 27.5 and 32 volts. Figure 6 provides FCP voltage as a function of power levels. As indicated, the FCP voltage degrades with active hours of FCP use. The caution and warning electronics are set at 25 volts. A new cell can provide 16 kilowatts, and an old cell can provide 12 kilowatts and maintain an output voltage above 27.5 volts. Figure 7 provides the predicted FCP voltage performance.

3.2 ATCS HEAT REJECTION

The ATCS heat transport and rejection must be adequate to reject the heat produced by the FCP and Orbiter equipment and provide an outlet return temperature of 39°F. The distribution of the heat must be monitored due to split flow, such as between the cabin interchanger and payload heat exchanger and multiple coolant loops. Radiators and flash evaporators are used to reject Orbiter/payload heat during flight. The radiator performance will vary depending on vehicle attitude, altitude, beta angle, and roll angle. For example, predicted radiator performance for +X on V attitude using the curves presented in figures 8 and 9 will vary from 35 to 140 000 Btu/hr. Backing up the radiators are the flash evaporators. The topping evaporator will normally provide additional cooling when heat loads

exceed radiator capacity. The topping evaporator is tested to reject approximately 40 000 Btu/hr, with additional radiator performance picked up when the evaporators are employed (fig. 10). The high-load evaporator is designed to reject approximately 100 000 Btu/hr. Both evaporators are limited by the potable water loaded on board and generated by the FCP (fig. 11). Extensive long-term usage of this system is therefore limited. Figure 12 presents the STS/OPS predicted heat load range versus FCP power level. Heat distribution around the ATCS loop will also limit the total power. The Consumables Analysis Section has made several runs, using the "SECRET" program, to identify where in the ATC loop one may expect design limit violation. Limits are encountered, depending on the state of the pertinent variables, at the midbody cold plate discharge temperature, at the fuel cell heat exchanger Freon 40 return temperature and in the ATCS heat rejections capability.

Figures 13 through 17 present the FCP power level limit dictated by ATCS constraints for an Orbiter/Spacelab configuration. These figures were generated using existing performance data for heat sinks and equipment operating limits using the "SECRET" program. The radiator capacity (ability to reject heat while maintaining a discharge temperature of 38°F) was varied between 10 000 and 150 000 Btu/hr as an analysis parameter, the same as the percent of power used by the Orbiter heaters. Table III presents a summary matrix of the integrated Orbiter FCP performance limits as determined by this analysis and includes only one point of reference for radiator performance taken from figure 8. As indicated by the SODB, the ATCS heat rejection can be a limiting factor to FCP power. Figures 8 and 9 were taken from reference 4. The curves in reference 4 were generated by the Mission Planning and Analysis Division with data provided by Engineering and Development Directorate for six attitudes, (X-POP, +X on V, +Z SI, -Z SI, -X SI, and +Y SI). Assuming the FES operation will be equal to water generation and operate jointly with the radiator, then the cooling limit on FCP power will vary from 14 to 48 kilowatts. There is, then, a flight design trade-off between power requirement and radiator environment. When high-power levels are required, a favorable radiator environment will also be required.

3.3 FUEL CELL LIFETIME

The fuel cell lifetime is degraded as a function of output versus time. Table I presents data for a fuel cell equivalent lifetime with and without maintenance. Maintenance may require that the cell be removed from the Orbiter. Table II presents the predicted fuel cell operation for the first 33 Shuttle flights taken from references 2 and 3. From table I, it can be seen that a new cell may require maintenance after 300 hours using 10 kilowatts continuously and be used for 758 hours with maintenance. Maintenance for each cell may be required several times to attain the 758 hours of useful lifetime. From the table, it can be seen that if a fuel cell were to supply 15 kilowatts continuously, its lifetime (without maintenance) would be less than 2 flight days.

4.0 CONCLUDING REMARKS

It is recommended that the FCP output limits as defined in reference 1 should be modified. A summary table of the fuel cell performance limits are provided in table III. This table indicates that a 36-kilowatt continuous output should be the upper limit. The predicted STS/OPS power requirements exceed the current FCP output limit defined in reference 1 but do not exceed the limits outlined in this document. The ATCS can maintain the FCP Freon 40 return temperature below its limit of 140°F while the FCP is providing 36 kilowatts continuously. At 36 kilowatts, the FCP voltage can be maintained above the 27.5-volt minimum limit if the distribution is equal for each fuel cell and each fuel cell has some of its 5000 hours of equivalent life (fig. 7) performance remaining. Two other FCP output limits are cooling and fuel cell lifetime. The cooling will depend on the radiator performance (environmental conditions) and the water available for supplemental cooling. The radiator/evaporator cooling could limit the FCP level to 14 kilowatts, however, in most attitudes the cooling will be able to cool the FCP loads at 36 kilowatts. Evaporator and ammonia boiler cooling will be adequate at 36 kilowatts if heater operation represents a high percentage of the total load, which currently is estimated (fig. 12). The fuel cell lifetime will depend on FCP power requirements. As mission power requirements are defined and growth occurs, an inherent monitoring of available cooling heater operation, and fuel cell lifetime will be required. With high FCP power requirements, increased maintenance must occur as well as a need for additional fuel cells.

5.0 REFERENCES

1. Shuttle Operational Data Book. JSC-08934 Vol. 1, Rev. A through Amendment 73, October 1976.

2. OFT Nonpropulsive Consumables Analysis. JSC IN 77-FM-7, Rev. 1, August

3. General Consumables Analysis for the First 26 Shuttle Orbiter Operational Flights. JSC IN 78-FM-57, October 1978.

4. Kolkhorst, H. E.: Orbiter Radiator Performance Data. Mission Planning and Analysis Division memorandum FM 26 77-197, November 22, 1977.

TABLE I.- FUEL-CELL LIFETIME CHART

Power average, kW	Lifetime (one cell) without maintenance, hr/kWh	Lifetime (one cell) with maintenance, hr/kWh
4.5	2000/9000	5 000/22 500
5	1535/7676	3 838/19 190
6	1047/6284	2 618/15 710
7	934/5138	2 336/12 845
8	551/4410	1 378/11 025
9	410/3694	1 025/9 235
10	303/3030	758/7 580
11	211/2326	528/5 815
12	143/1716	357/4 284
15	46/690	116/1 740

TABLE II.- PREDICTED FLIGHT FCP POWER REQUIREMENTS
FOR THE FIRST 33 MISSIONS

Flight	Duration, days	kWh	Individual cell average, kW
1. STS-1	2	1 056	7.3
2. STS-2	5	2 070	5.8
3. STS-3	7	2 936	5.8
4. STS-4	7	2 511	5.0
5. STS-5	7	2 766	5.5
6. STS-6	7	2 678	5.3
7. TDRS A	2	832	5.8
8. SBS-A/GOES-D/ANIK-C/1	3	1 283	5.9
9. STP-P80-1/SMM/SPAS-C1	3	1 251	5.8
10. TDRS B	1	562	7.8
11. Spacelab 1	7	3 417	6.8
12. INSAT-1A/SBS-B/RCA-C	3	1 273	5.9
13. TDRS-C/ANIK-C/2	2	887	6.2
14. Intelsat V/GOES-E	2	874	6.1
15. LDEF deploy/SMM retrieval	3	1 179	5.5
16. Spacelab 2	9	3 646	5.6
17. TDRS-D/IND MODE	2	954	6.6
18. Galileo	1	562	7.8
19. Spacelab 3	8	4 046	7.0
20. ZOHREH-1/INSAT 1B/INDMODB	3	1 578	7.3
21. Spacelab 4	7	3 521	7.0

TABLE II.- Concluded

Flight	Duration, days	kWh	Individual cell average, kW
22. DOD-82-1	1	562	7.8
23. Spacelab 5	10	6 044	8.4
24. ZOHREH-2/GOES B/U	2	872	6.1
25. Spacelab 6	10	5 108	7.1
26. DOD-82-2	1	562	7.8
27. Intelsat V/MAT science/IND MODE	7	2 899	5.8
28. SBS-C (B/U/ANIK-C/3(B/U)	2	871	6.0
29. Spacelab 7	10	5 083	7.1
30. Repeat flight 14	2	874	6.1
31. Spacelab 8	7	3 166	6.3
32. LDEF retrieval/payload of OPP	7	2 740	5.4
33. Spacelab 9	7	3 596	7.1
Total	157	72 262	6.4

TABLE III.- FCP OPERATING LIMITS SUMMARY
FUEL CELL OPERATING LIMITS

	1 fuel cell, kW	2 fuel cells, kW	3 fuel cells, kW
Thermal (FCP inlet/outlet)			
w/o heater/2 STC's loops[a]	NA	NA	38
w/25% heater/2 ATCS loops	NA	NA	48
w/o heaters/1 ATCS loop[a]	13.5	16.5	18.5
w/25% heaters/1 ATCS loop	17	22	24
Voltage output (27.5 V d.c.)			
Steady state new cell	16	32	48
Steady state 5000-hr cell	12	24	36
2 ATCS loop heat rejection Attitude +X on V; B = 0° h = 150 mi; panels = 8; roll = 180° radiators alone			
w/o heaters	13	13	13
w/25% heaters	16	16	16
Radiators with topping evaporator assuming: water used = water generated			
w/o heaters	NA	24	24
w/25% heaters	NA	32	34
Topping and high-load evaporators			
w/o heaters	NA	NA	27
w/25% heaters	NA	NA	33

[a]Assumes ATCS Freon 21 flow rate of 5590 for two loops and 2795 for one loop (Spacelab configuration).

[b]Not applicable.

TABLE III.- Concluded

	1 fuel cell, kW	2 fuel cells, kW	3 fuel cells, kW
Ammonia boiler			
w/o heaters	NA	NA	23.4
w/25% heaters	NA	NA	30.0
ATCS other equipment limits (Midbody cold plates)			
With 2 ATCS loops			
w/o heaters	30.5	30.5	30.5
w/25% heaters	41.0	41.0	41.0
With 1 loop			
w/o heaters	14.0	14.0	14.0
w/25% heaters	16.5	18.0	18.0

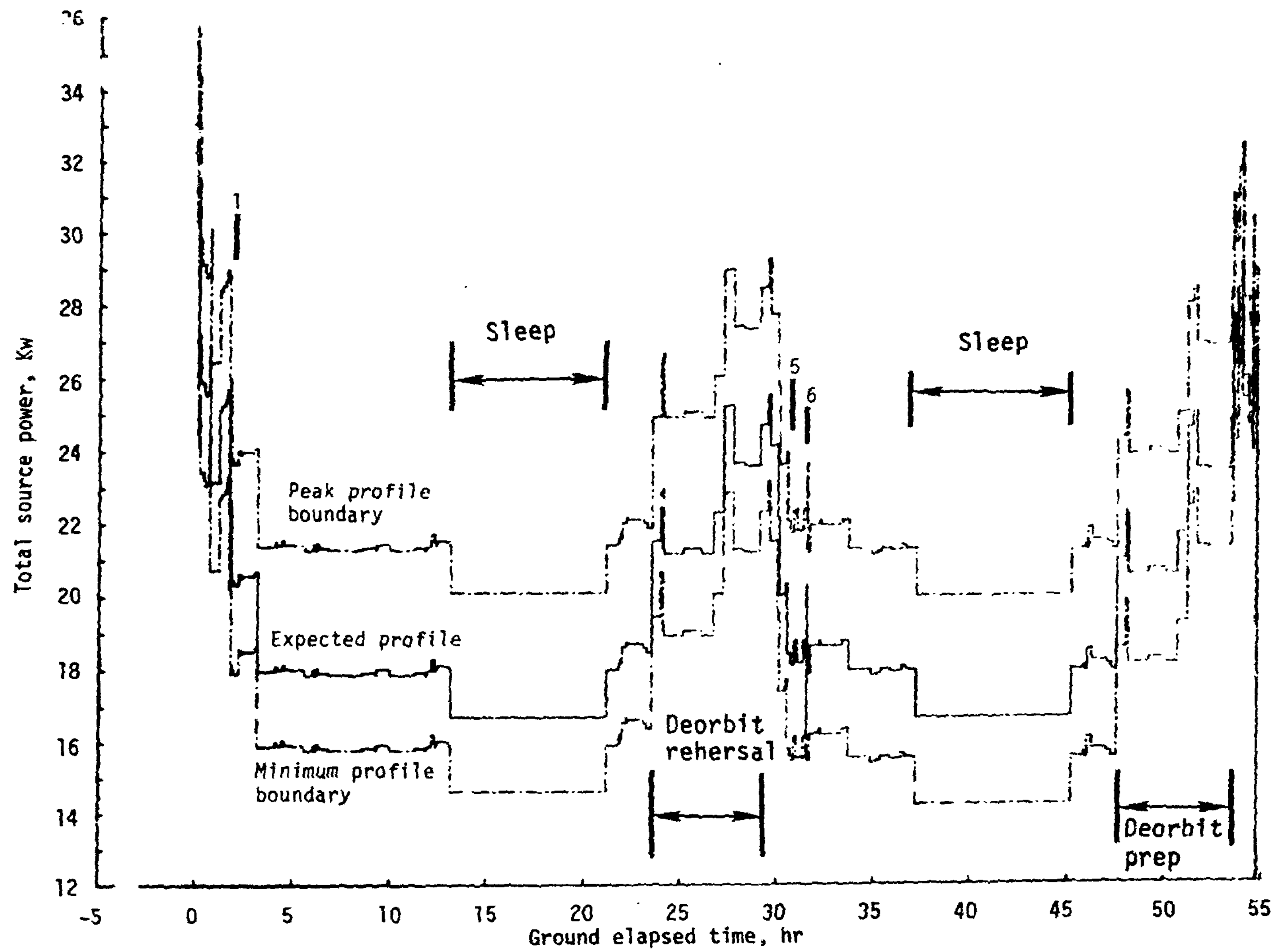
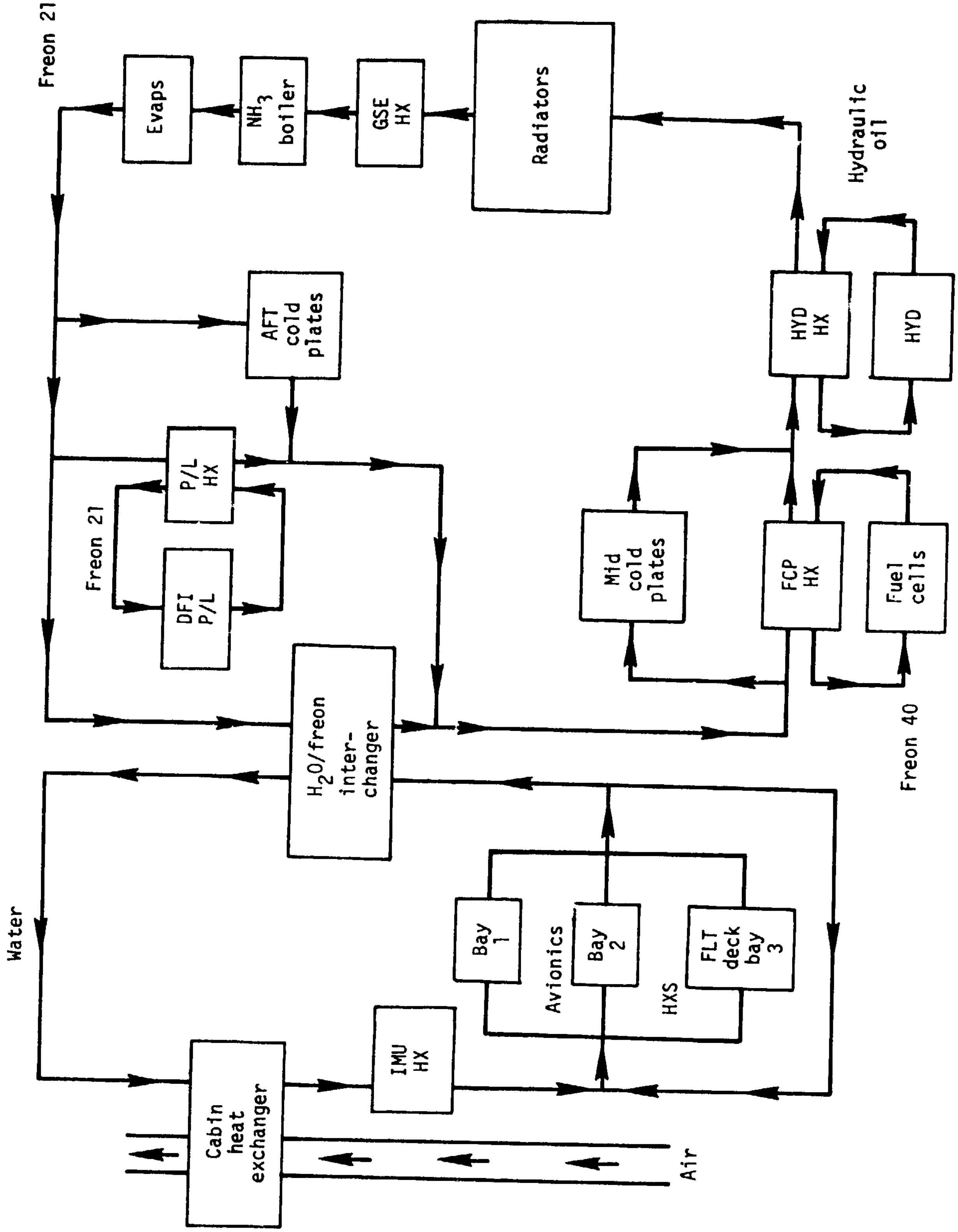


Figure 1.- Total source power profiles for STS-1.



Freon 21
Evaps
NH3 boiler
GSE HX
Radiators
Hydraulic oil
AFT cold plates
HYD HX
HYD
P/L HX
Freon 21
DFI P/L
Mid cold plates
FCP HX
Fuel cells
Freon 40
H2O/freon inter-changer
Water
Bay 1
Bay 2
FLT deck bay 3
Avionics
HXS
IMU HX
Cabin heat exchanger
Air

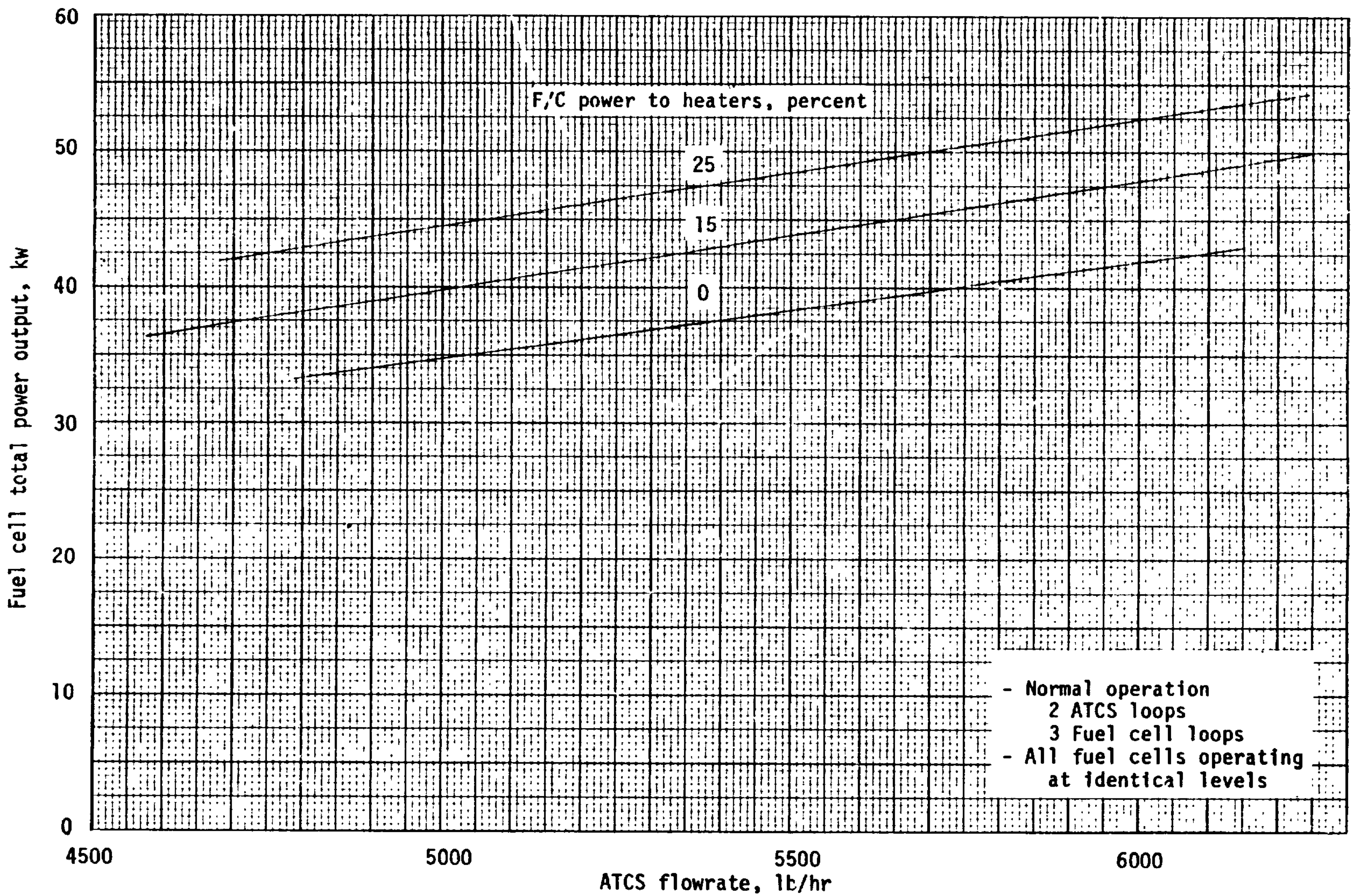


Figure 3.- Maximum permissible fuel cell power level while maintaining fuel cell coolant within temperature specification.

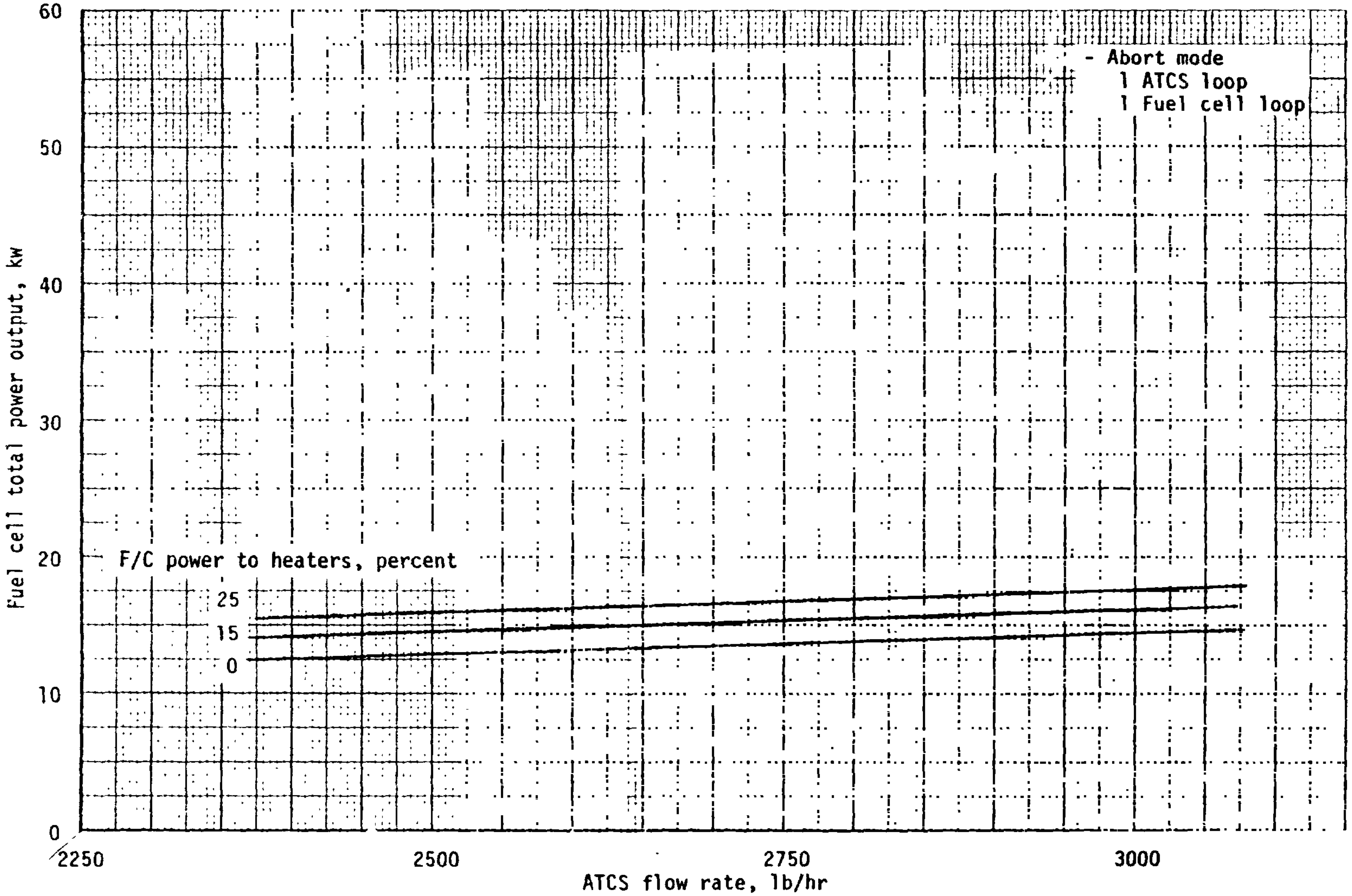


Figure 4.- Maximum permissible fuel cell power level while maintaining fuel cell coolant within temperature specification.

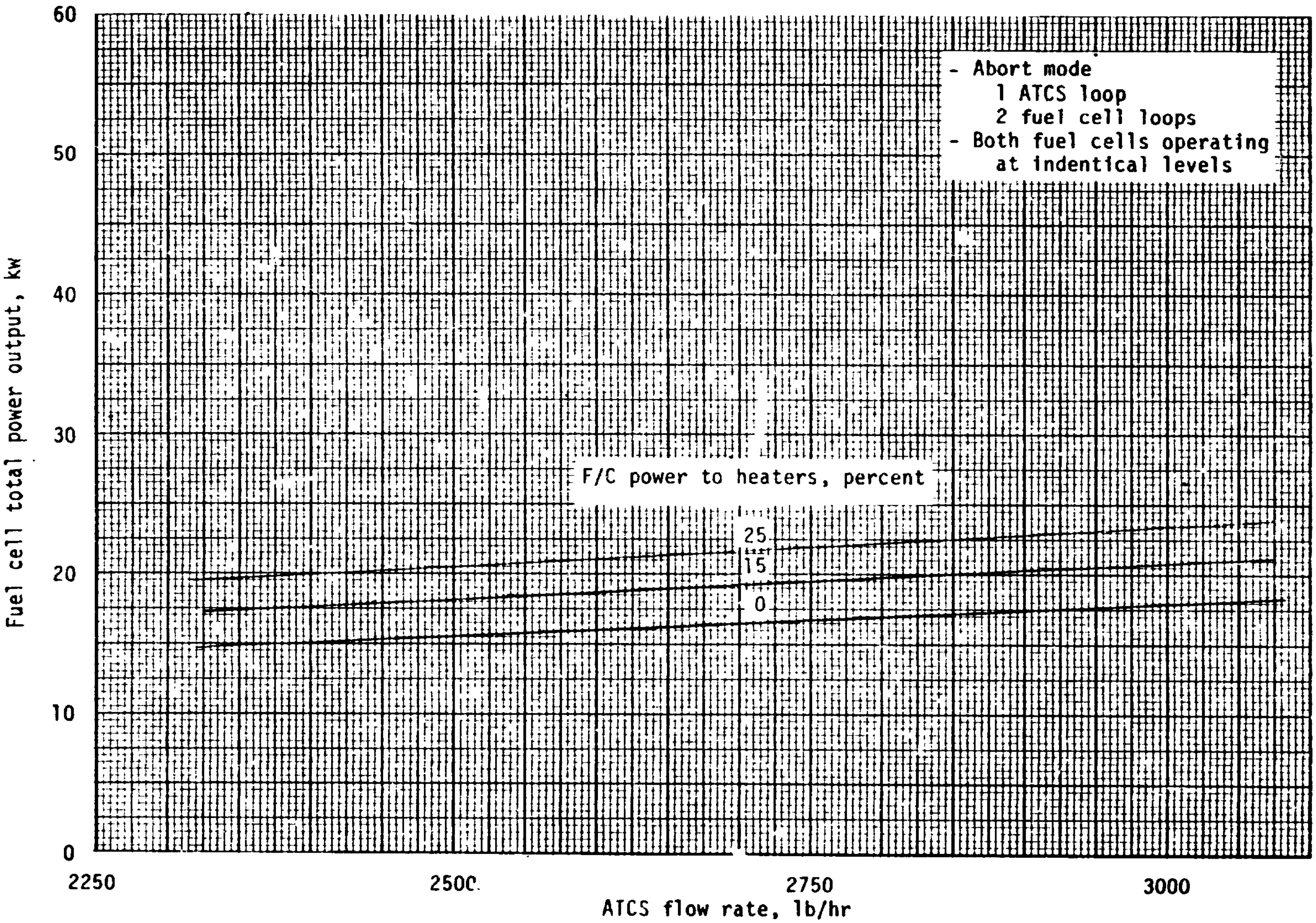


Figure 5.- Maximum permissible fuel cell power level while maintaining fuel cell coolant within temperature specification.

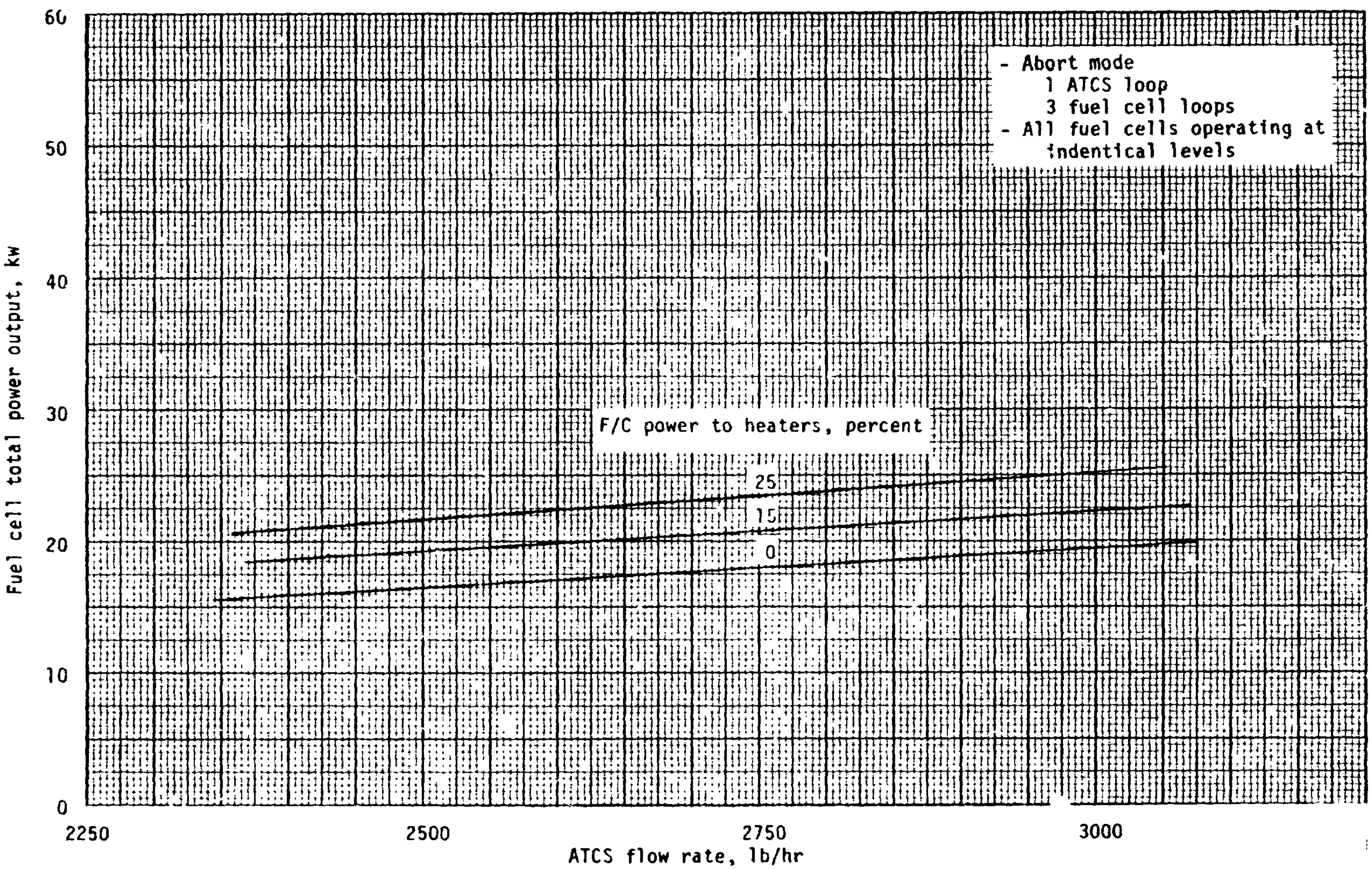


Figure 6.- Maximum permissible fuel cell power level while maintaining fuel cell coolant within temperature specification.

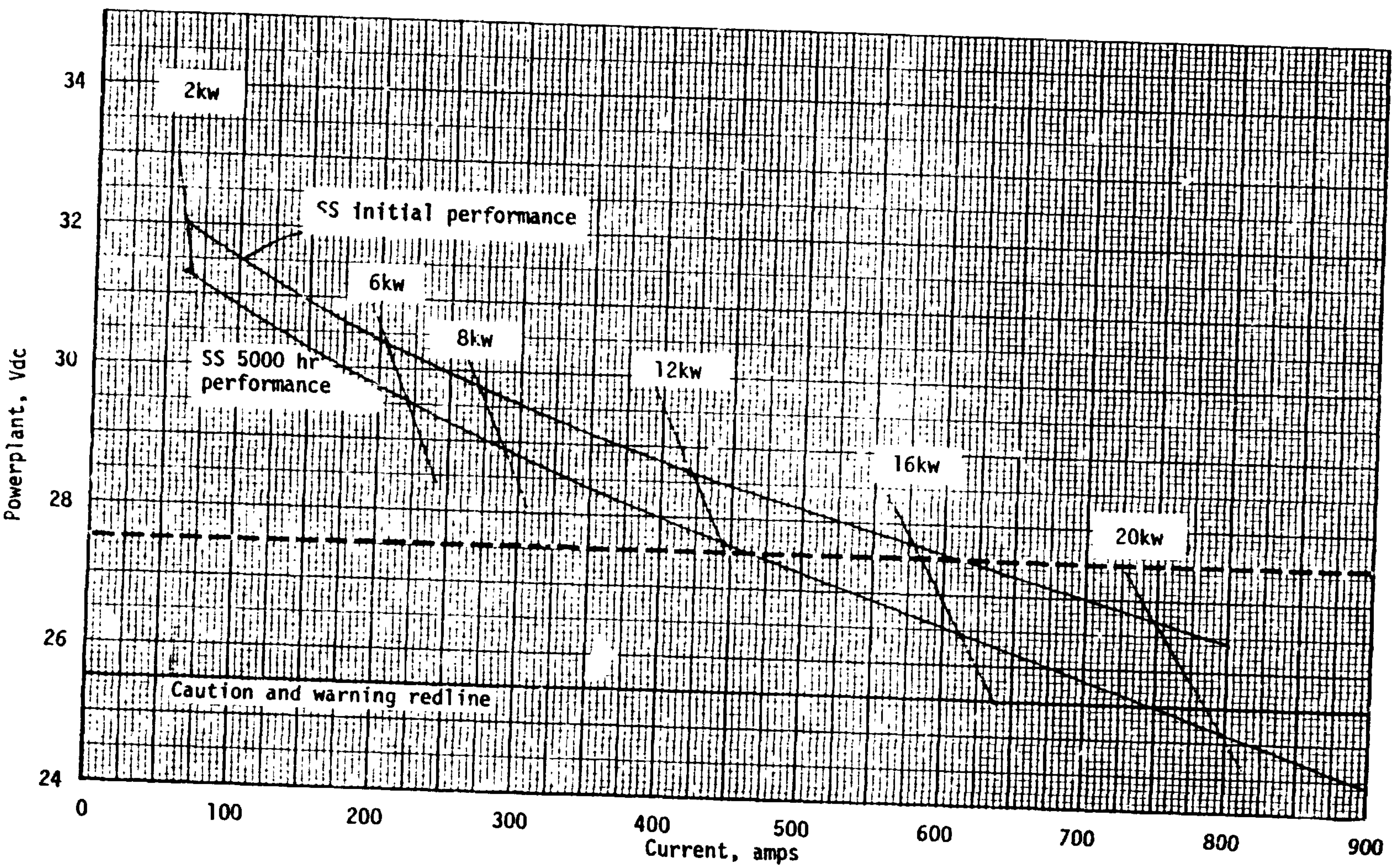


Figure 7.- Predicted single fuel cell powerplant performance.

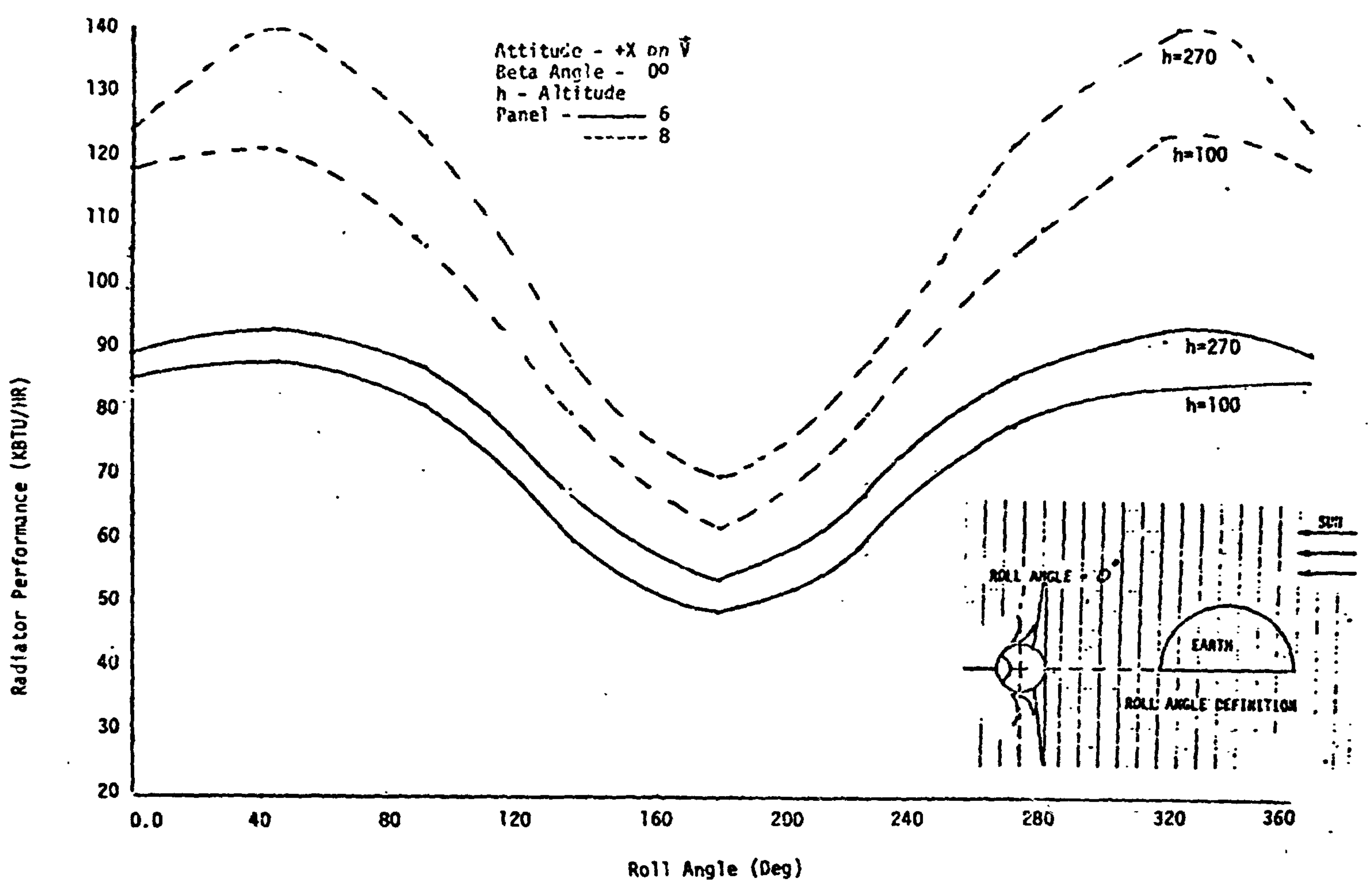


Figure 8.- Radiator performance integrated ov_r orbital position for the +X on $\vec{V}$ attitude.

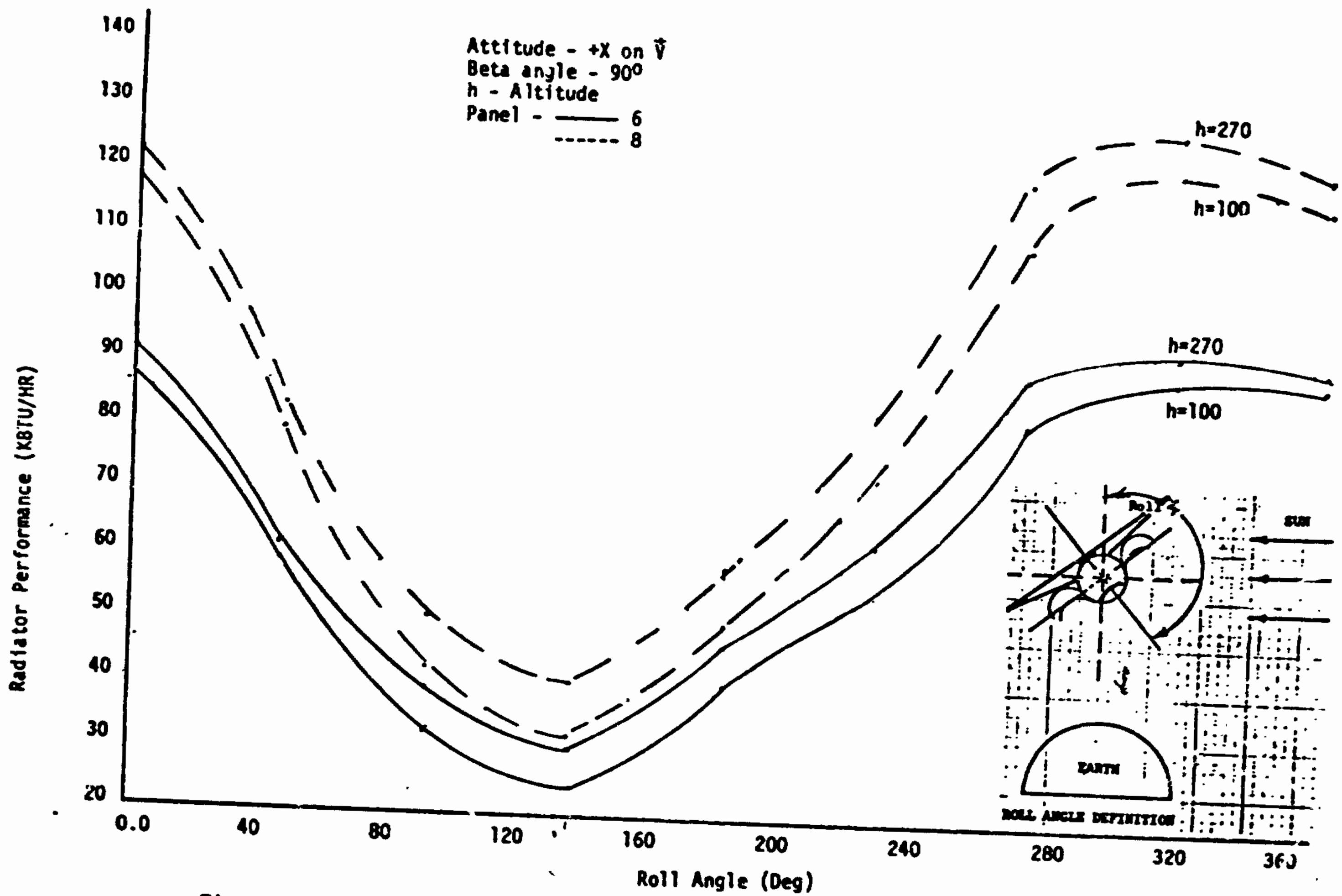


Figure 9.- Radiator performance integrated over orbital position for the +X on $\vec{V}$ attitude.

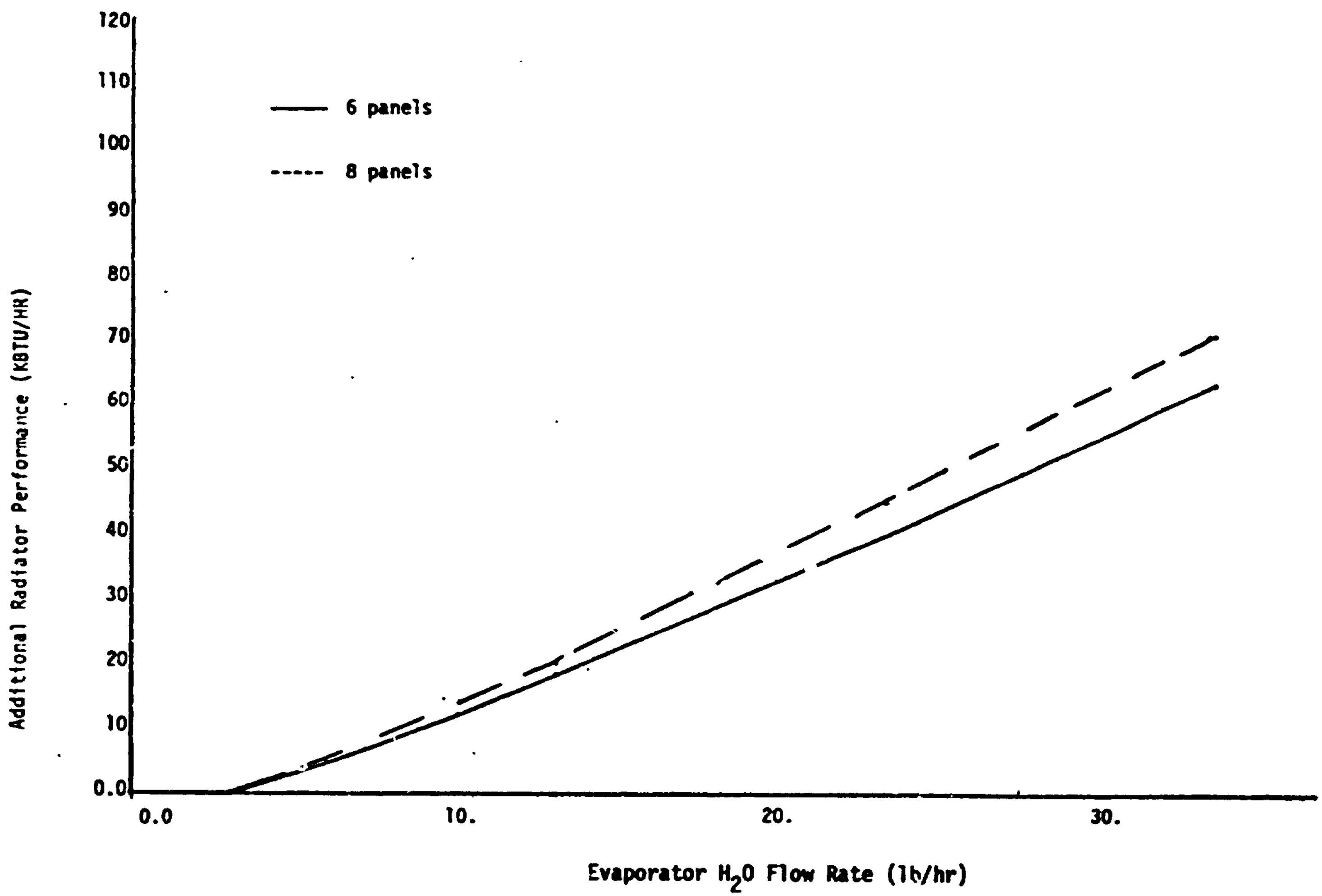


Figure 10.- Additional radiator performance with evaporator flow rate

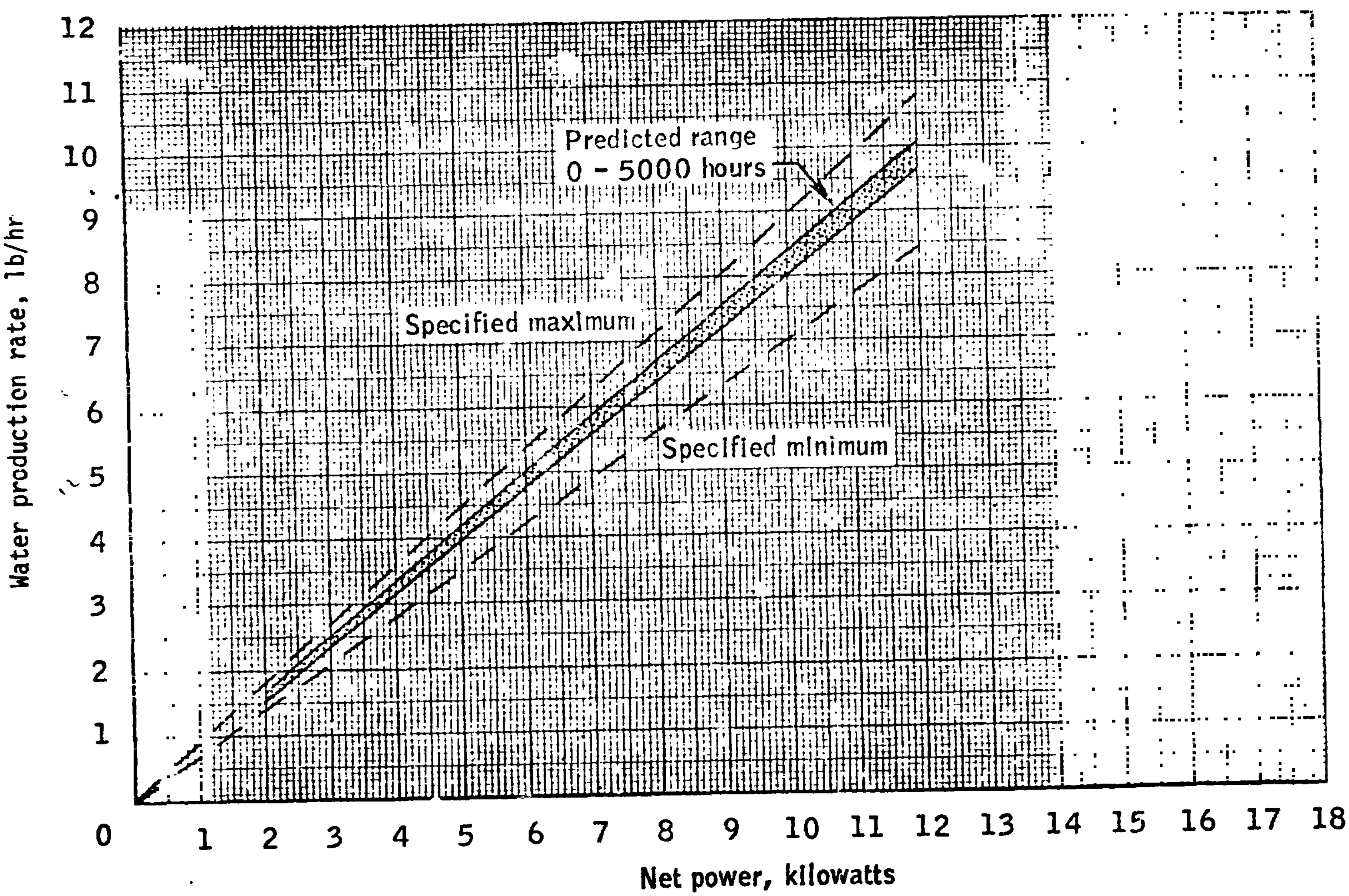


Figure 11.- Water production rate per fuel cell powerplant.

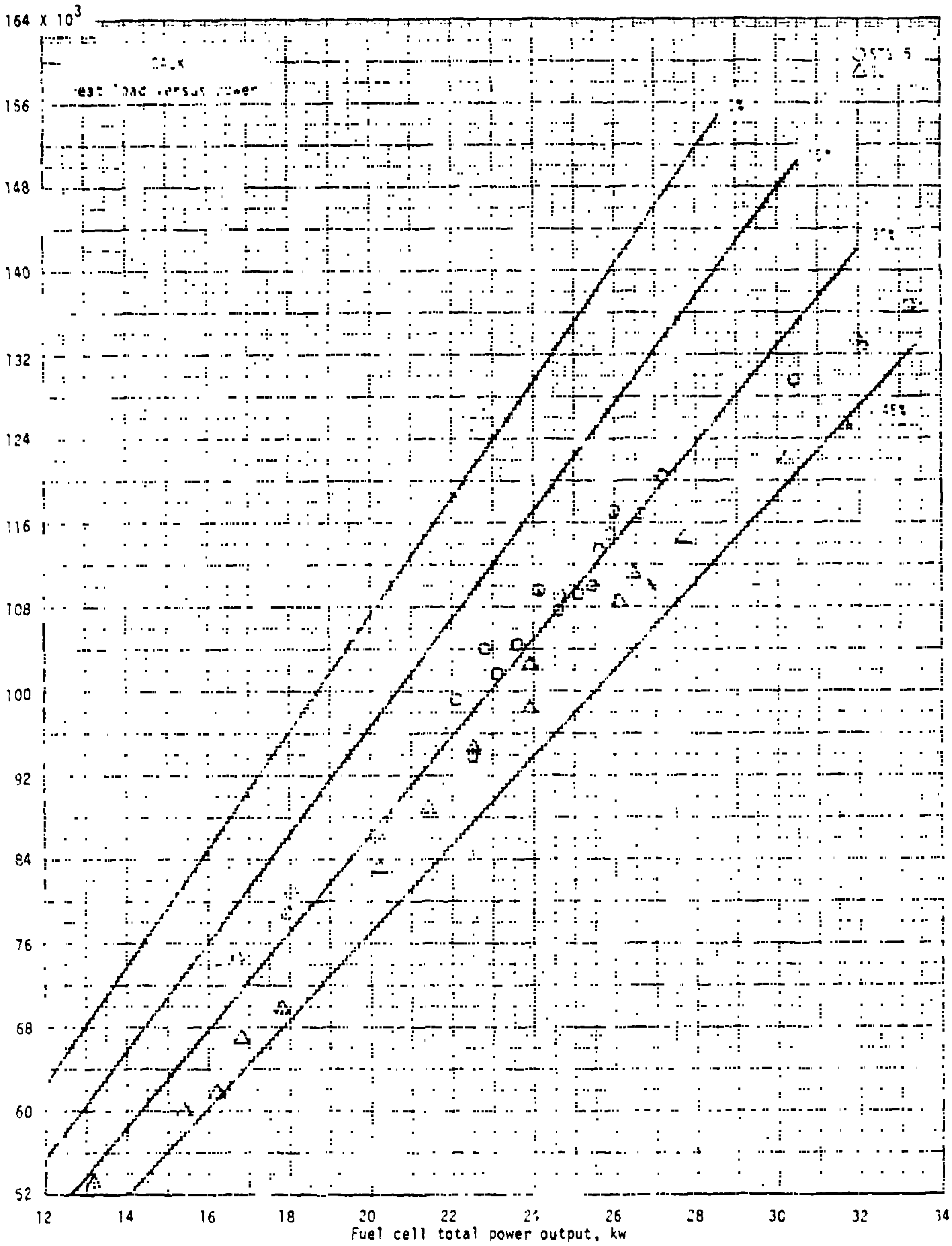


Figure 12.- STS/OPS predicted heat load range versus power level.

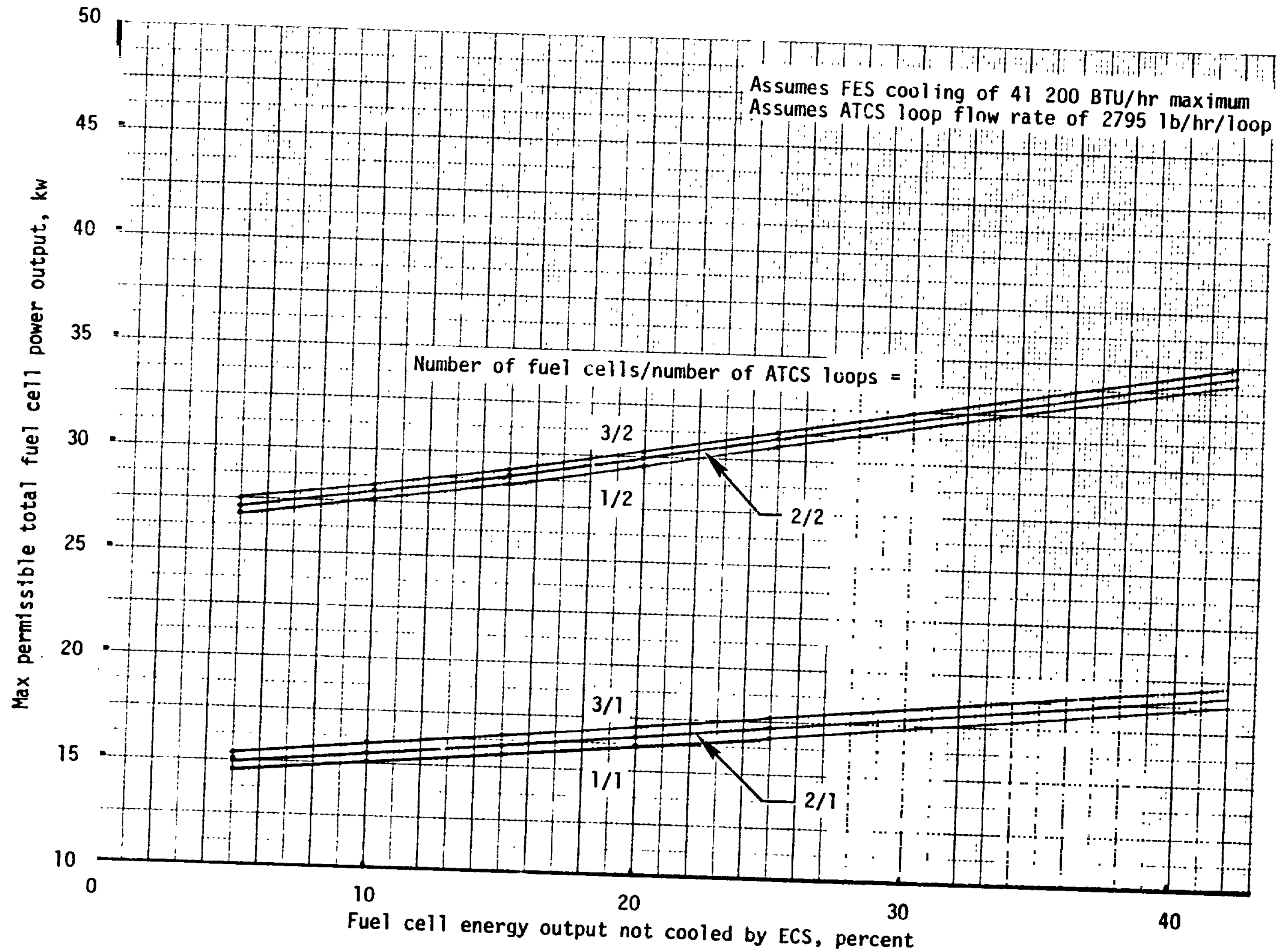


Figure 13.- Fuel cell steady-state power limits determined by ATCS thermal considerations with full radiator bypass at various fuel cell/ATCS loop configurations.

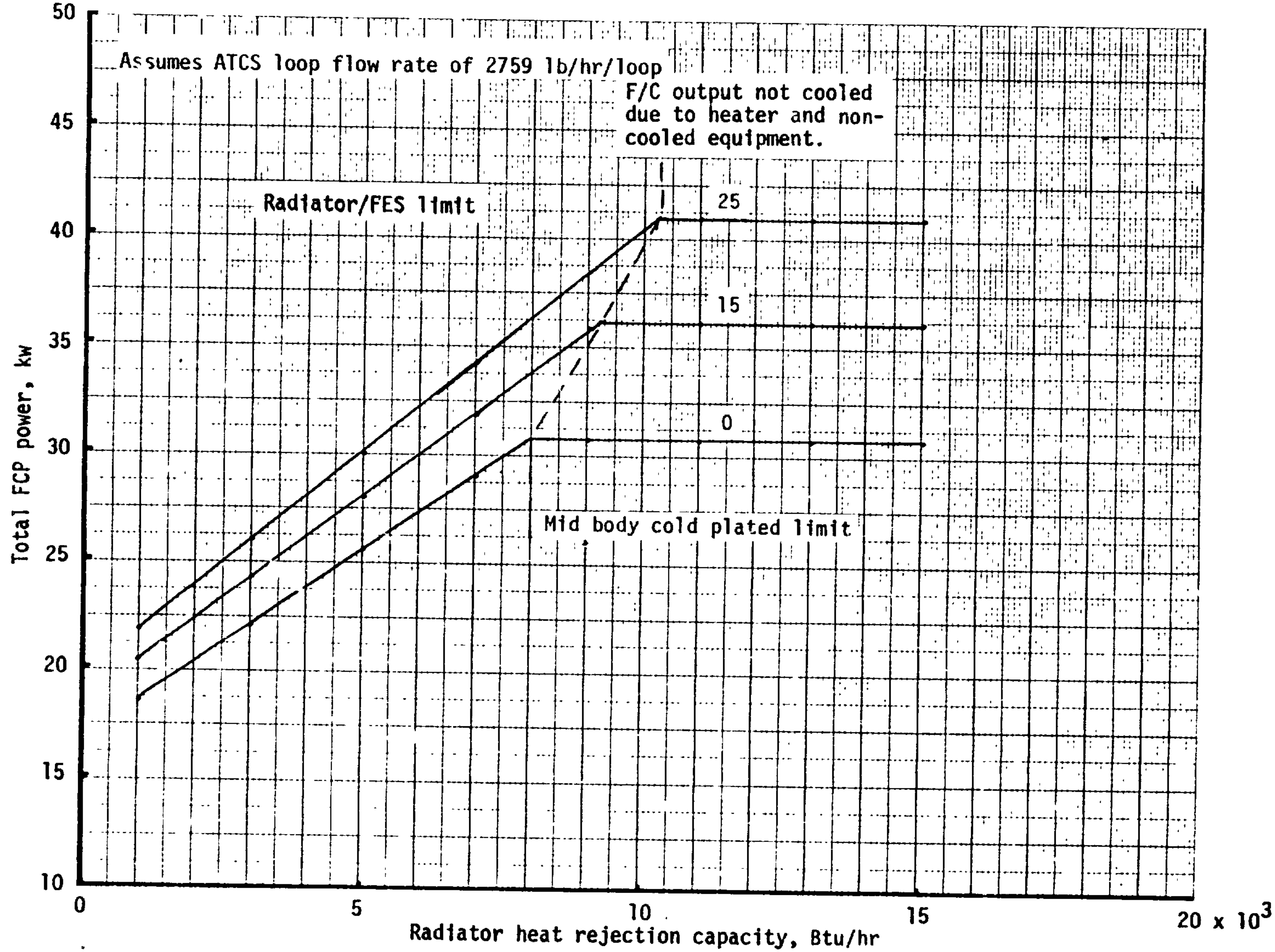


Figure 14.- Fuel cell steady-state power limits determined by ATCS thermal considerations using radiator cooling and supplemental flash evaporator cooling of 41 200 Btu/hr max using 3 fuel cells and 2 ATCS loops.

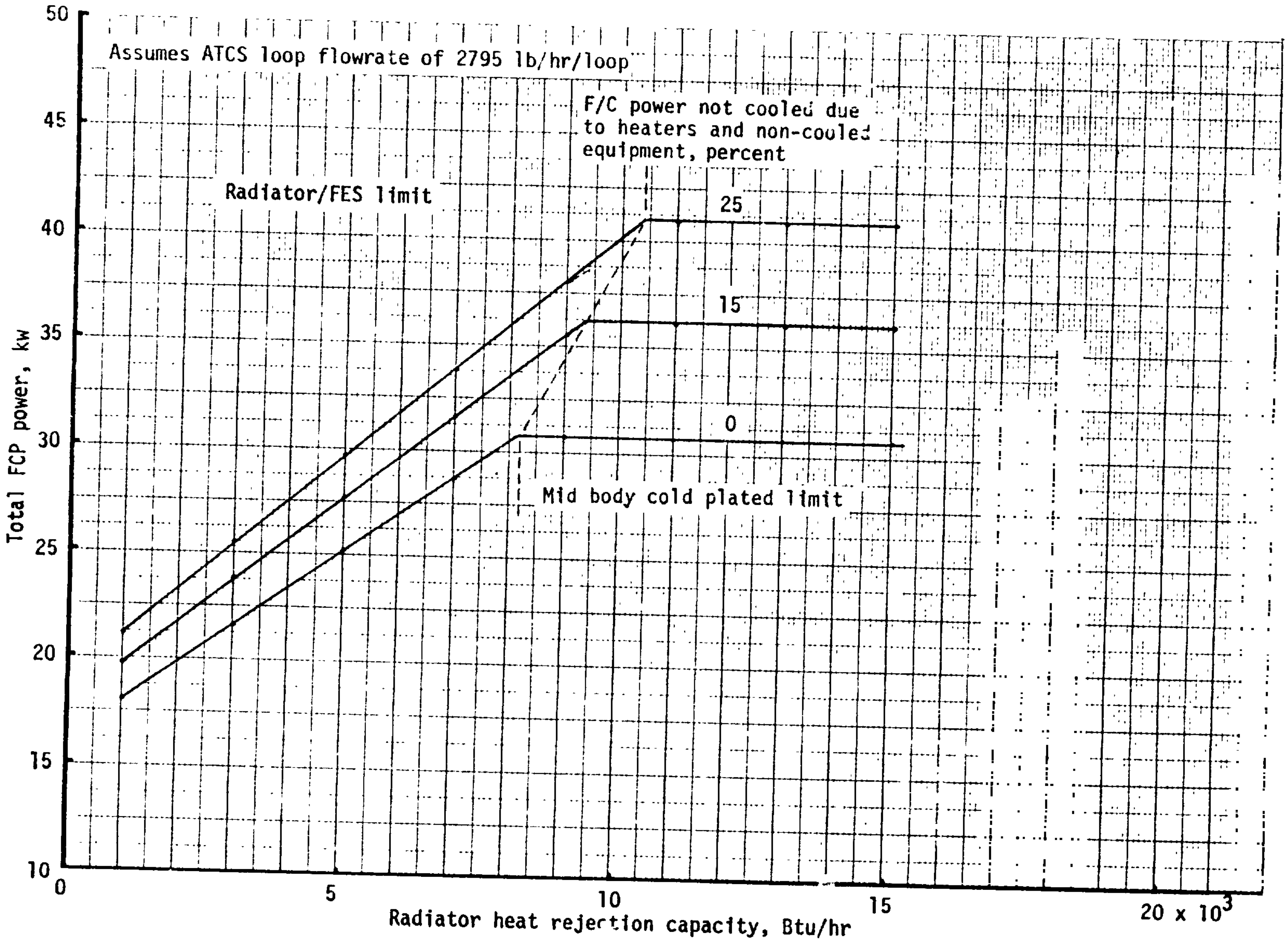


Figure 15.- Fuel cell steady-state power limits determined by ATCS thermal consideration using radiator cooling and supplemental flash evaporator cooling of 41 200 Btu/hr max using 2 fuel cells and 2 ATCS loops.

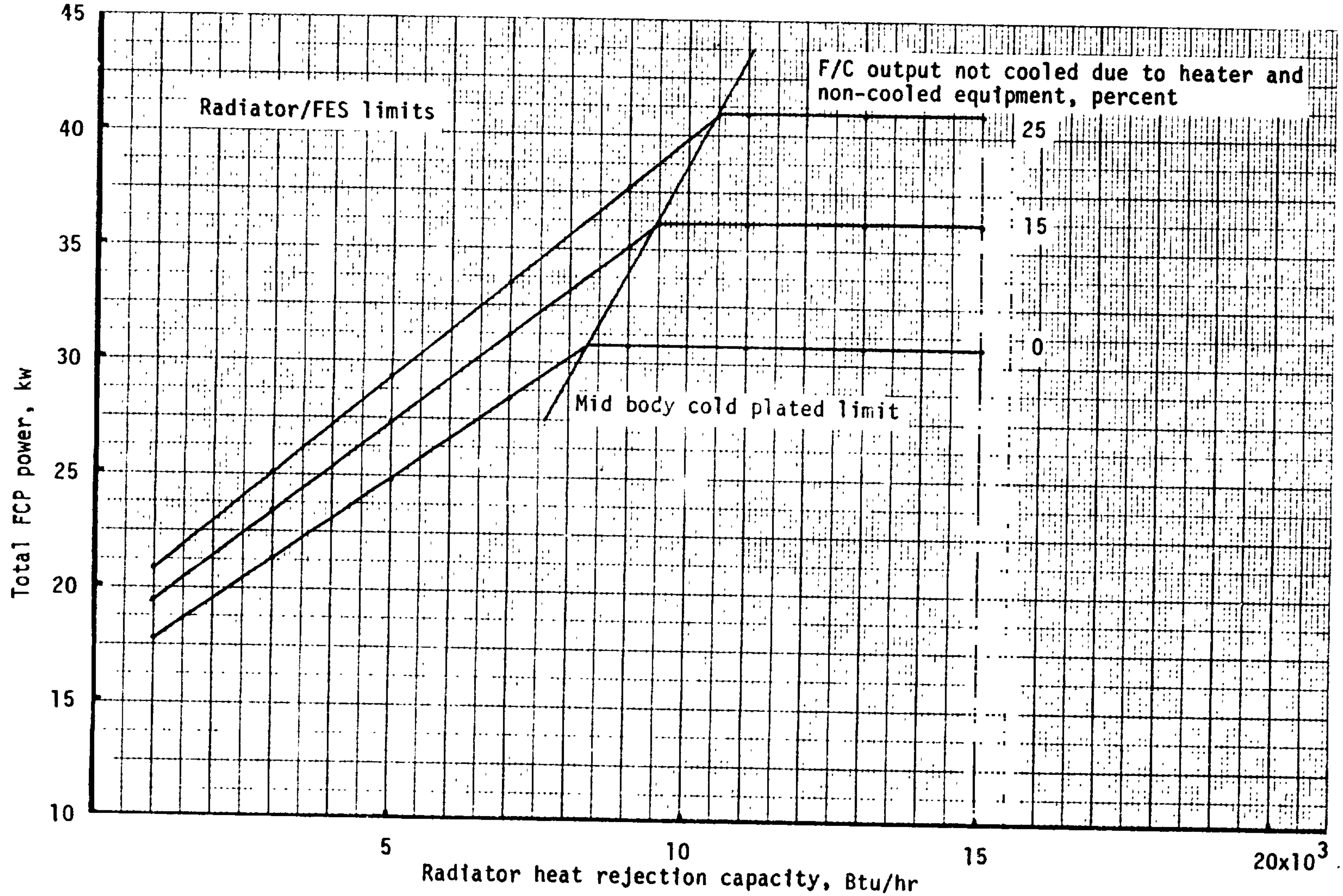


Figure 16.- Fuel cell steady-state power limits determined by ATCS thermal considerations using radator cooling and supplemental flash evaporator cooling of 41 200 Btu/hr max using 1 fuel cell and 2 ATCS loops.

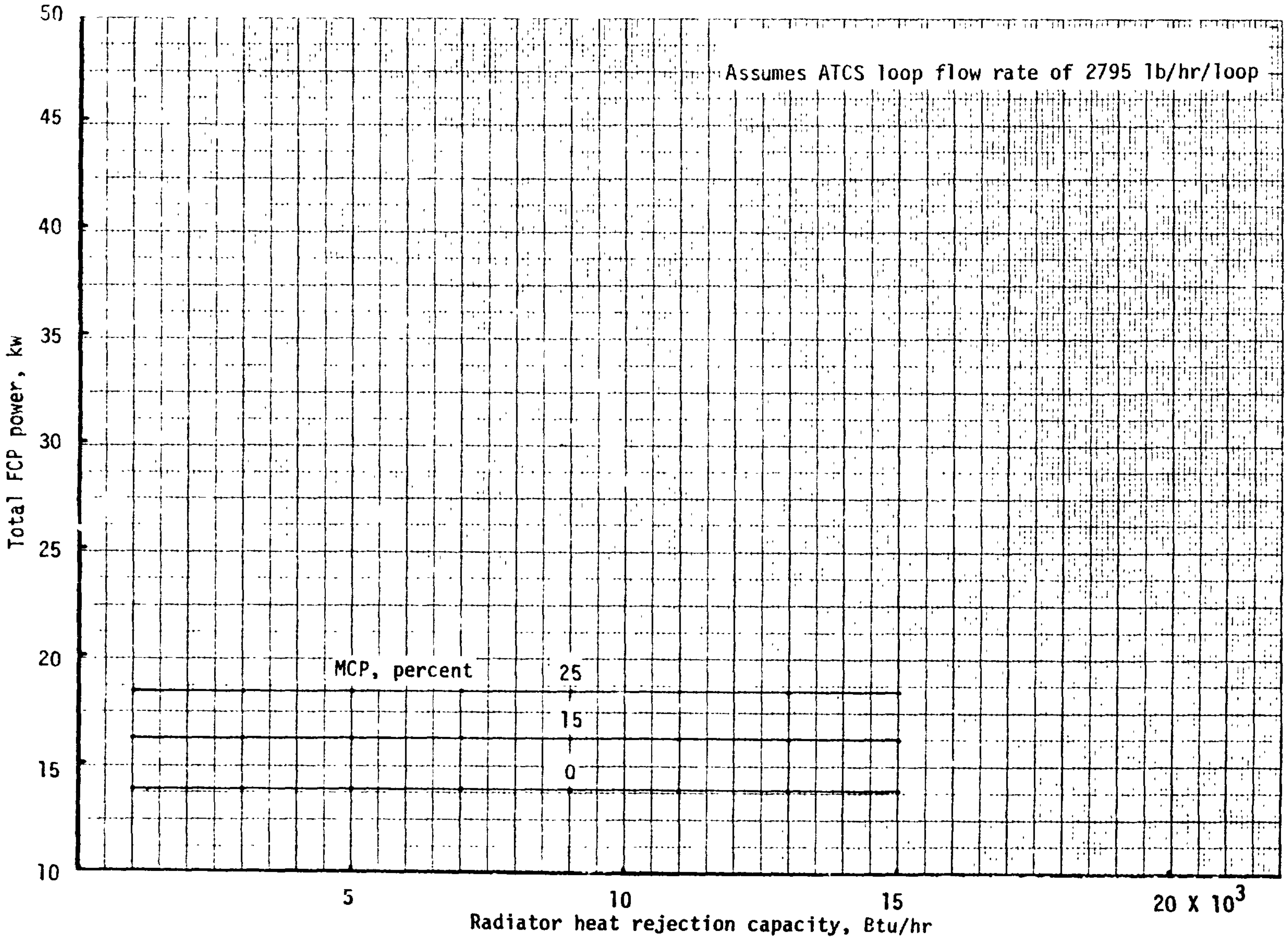


Figure 17.- Fuel cell steady-state power limit determined by the midbody cold-plated thermal limit using one ATCS loop for both 3 and 2 fuel cells operating.

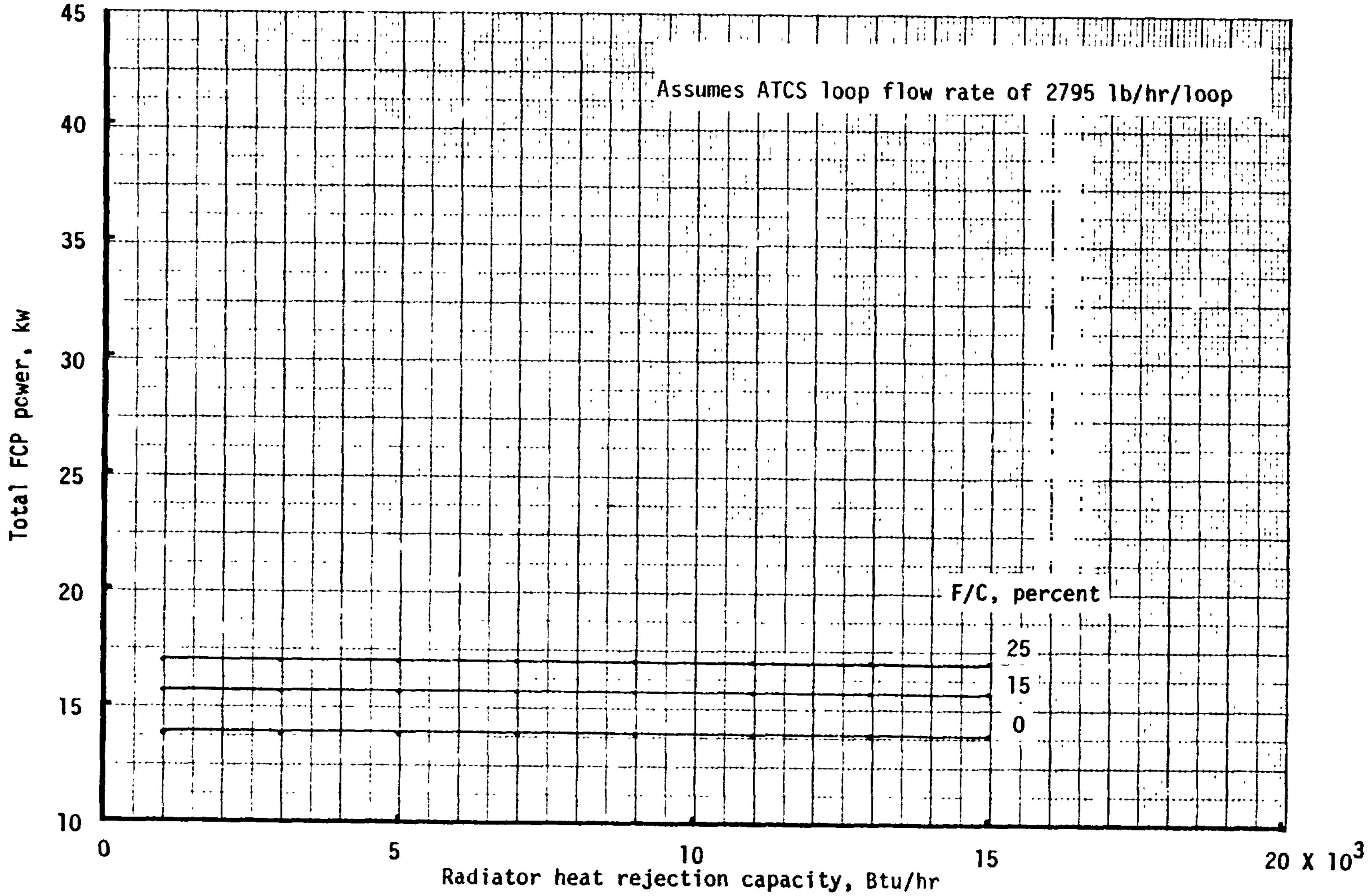


Figure 18.- Fuel cell steady-state power limit determined by the midbody cold-plated thermal limit using one ATCS loop for one fuel cell operating.

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